MEASUREMENT AND PREDICTION OF ATOMIZATION PARAMETERS FROM FIXED-WING AIRCRAFT SPRAY NOZZLES

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ABSTRACT. *A survey of spray nozzles used by the agricultural aviation industry identified nozzles and operating conditions that were most commonly used in applying agricultural chemicals in the U.S. Eleven hydraulic nozzles and their typical range of operating conditions were selected from the survey. These eleven nozzles were subjects of a research program to develop spray atomization models that would be easy for aerial applicators to use in adjusting operations to control spray drift from aerial agricultural sprays. Each nozzle was conducted through a series of trials in a spray nozzle test facility equipped with a laser spectrometer to develop a data set for atomization model development. Computer spreadsheet models were developed from the data set with operator selection of a specific spray nozzle and inputs of nozzle orifice size, spray discharge angle, spray pressure, and aircraft airspeed. The model outputs included droplet size parameters, drift potential parameters, and droplet spectra classification. Aircraft speed was the dominating factor influencing atomization from most of the spray nozzle models. Validation studies showed that the models gave useful estimates of the computed parameters for estimating compliance with product label and state regulatory agency requirements for spray drift mediation. The models are available on-line and in a user handbook as well as in the current technical presentation.*

Keywords. *Aircraft, Nozzles, Spray, Droplets, Models.*

The agricultural aviation industry has long been interested in atomization characteristics of the spray nozzles used on agricultural aircraft. Early interest in droplet size and droplet density was related to their influence on efficacy of crop production and protection materials. More recent concerns about spray drift and environmental trespass have heightened interest in characteristics of sprayed materials as related to spray drift. Droplet size and spray droplet spectra are the dominant factors in determining spray drift, with small droplets more prone to drift from the application zone than large droplets.

The agricultural chemical industry responded to a call from the U.S. Environmental Protection Agency (EPA) for spray drift data for major agricultural chemicals. The industry created the Spray Drift Task Force (SDTF), which was composed of and supported a broad range of industry and academic scientists and engineers. The industry funded extensive research to document procedures and collect data for estimating spray drift from various spray application methods. This industry initiative ultimately led to a cooperative research and development agreement involving the SDTF, the EPA, and the USDA to develop information on spray drift that could be used by regulators, agricultural chemical companies, and pesticide applicators to reduce incidents of damaging spray drift. A technical committee of ASABE, through its Cooperative Standards Program, subsequently developed a standard for classifying agricultural sprays, ASAE S572 (Womac et al., 1999; *ASAE Standards*, 2004).

Considerable data are available on aerial spray droplet spectra from different nozzles operating under various conditions (Akesson, 1954; Akesson and Gibbs, 1990; Bouse, 1994; Hewitt, 1995a, 1995b, 1997, 2001; Picot et al., 1990; Skyler and Barry, 1990, 1991; Yates et al., 1985). However, these early data are of limited usefulness to aerial applicators in determining droplet spectra classifications (DSC) as specified in ASAE S572 for a given application because the data were collected and published before the original publication of ASAE S572, which defined procedures for obtaining DSC. The early publications primarily used volume median diameter ($D_{V0.5}$) for characterizing spray droplet spectra rather than the more encompassing and conservative DSC as defined in ASAE S572.

The SDTF collected atomization data on numerous spray nozzles and developed atomization models to represent the spray nozzles in their study (Hermansky, 1998; Hewitt, 2001). However, between the time the SDTF selected nozzles to study and the completion of their data collection, an industry phenomenon occurred: aerial applicator use of the CP-03 nozzle increased from less than 5% to over 60% market penetration. The CP-03 nozzle was not in the SDTF dataset, and the associated contracts were completed, but the need for atomization data for the CP-03 nozzle was readily apparent. Consequently, a study was conducted to develop data for the CP-03 aerial spray nozzle (Kirk, 1997).

The easy-to-use model from that study led industry leaders in the National Agricultural Aviation Association (NAAA) to call for additional models that included the nozzles most commonly used in the industry. Consequently, the NAAA and the USDA conducted a survey of aerial applicators to determine the spray nozzles in most common use by the aerial application industry. Aerial spray nozzles with

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Table 1. Spray nozzles selected for aerial performance modeling in this study.

Nozzle Type	Orifice Size Range
40° flat-fan (small orifice, brass)	4002 - 4010
40° flat-fan (large orifice, brass)	4010 - 4030
80° flat-fan (brass)	8002 - 8010
CP-03 (poly)	0.061 - 0.171 in.
CP-09 (stainless)	0.061 - 0.171
CP-11TT (with straight-stream tips, stainless)	0008 - 0025
Disc orifice with 46 core (ceramic)	2 - 10
Disc orifice with 46 core (stainless)	2 - 10
Disc orifice with 56 core (stainless)	2 - 10
Disc orifice straight-stream (stainless)	4 - 12
Lund straight-stream (stainless)	6 - 10

greater than 5% market penetration from the survey were selected for model development in this study of the fixed-wing segment of the industry. A few nozzles of special interest because of their unique design or atomization profiles were also included in this study. Some nozzle models (Kirk, 1998, 1999) were developed prior to the original publication of ASAE S572. The earlier models in this series, including the models for the rotary-wing segment of the industry (Kirk, 2002), were subsequently modified to comply with ASAE S572. Eleven fixed-wing aerial spray nozzle models were developed from a series of studies (table 1) and are reported herein.

Objective

The objective of this study was to develop computerized atomization models for estimating droplet size as volume median diameter ($D_{V0.5}$), relative span (RS), droplet spectra classification (DSC), and percentage of the spray volume in droplets less than 100 μm diameter (%V<100 μm) and less than 200 μm diameter (%V<200 μm) for eleven spray nozzles operating under conditions commonly used in fixed-wing aerial applications. A criterion for the models was that they could be easily used by aerial applicators to determine DSC from their applications if required by either crop protection product labels or state regulatory agencies.

Equipment, Materials, and Methods

This study was conducted in accordance with the specifications and intent of ASAE S572 as was reasonably possible. It is important to note that the primary or intended use of ASAE S572 is for ground application ("discharge in static air") rather than aerial application, for "relative nozzle comparisons based on droplet size only," and several other listed factors "not addressed by the current Standard." With these reservations noted by the Standard, and a study objective of providing reasonable applicability to real-world agricultural aerial applications, considerable professional judgment and decisions were necessary to comply with the intent of the Standard and yet provide usable data for aerial applicators. For example, data for the reference nozzles were first collected and recorded according to the Standard. None of the reference nozzles are classified as drift reduction nozzles and were thus run only with water.

However, since drift can be a problem with aerial application, and since surfactants generally reduce droplet size and increase drift potential, all of the nozzles classified in the study were run with a surfactant because surfactants are commonly used in pesticide formulations and in aerial agricultural chemical spray mixes. The surfactant selected for use in the study was a common agricultural chemical surfactant, rather than the scientific-industrial surfactants noted in the Standard, i.e., isopropanol (an industrial cleaning solvent and the primary ingredient in rubbing alcohol) or Surfynol TG-E (used primarily for water-based pigment-containing coatings). The spray mixture for all of the classified nozzles was thus tap water plus an agricultural surfactant.

The Standard imposes a conservative position relative to nozzle classification and spray drift by using a surfactant for classifying nozzles where spray drift may be an issue and by using one standard deviation above the threshold curve for the upper limit of each reference nozzle curve for classifying nozzles. The reference nozzles were classified with water as the spray liquid and in still air as the test condition, whereas the nozzles to be classified were classified with an agricultural surfactant in water and at reasonable airspeeds for fixed-wing aerial agricultural applications.

In addition, while the procedures outlined in the Standard were used with the reference nozzles, longer atomization distances and a modified laser traversing protocol were used for the nozzles classified in the air stream to permit the spray plume to fully develop and be properly scanned. Otherwise, the procedures of ASAE S572 were followed for both the reference nozzles and the nozzles to be classified. These kinds of decisions and modifications were reasonable and necessary to ensure usable data for the aerial agricultural chemical application industry and still reasonably comply with the intent of the Standard.

Agricultural spray mixes are generally dilute water-based mixtures containing the active ingredient with its associated formulation components. Surfactants are usually included in the formulation, and operators often add additional surfactants to the spray mixture. An active ingredient was not included in the spray mixture for these studies. The spray mixture for all of the nozzle classification studies was tap water plus 0.25% v/v Triton X-100 (Rhom and Haas), a nonionic surfactant commonly used in agricultural chemical formulations. The dynamic surface tension of the spray solution for classifying the aerial nozzles was 44 dynes/cm at 20 ms rather than the 40 ± 2 dynes/cm at 10 to 20 ms specified in the Standard. Dynamic surface tension is the only spray mix property referenced in the Standard.

Test Setup

An agricultural aircraft spray nozzle test facility, previously described by Bouse and Carlton (1985) and Bouse (1994), was used to conduct the study. The test facility included an engine-driven centrifugal fan with a tapered exit transition to a 30 cm square outlet. The transition was equipped with multiple internal tubes to straighten the airflow in the test section. The square outlet was fitted with an airfoil-shaped horizontal spray boom section with a centrally located spray nozzle port. Airspeed was controlled by engine speed and was measured in the air stream with a Pitot tube and aircraft airspeed indicator. A PMS laser spectrometer system (OAP-2D-GAI probe and PC-compatible OAP-1000 data acquisition system, Particle Measurement Systems, Inc., Boulder, Colo.) was used to collect atomization data. ASAE S572 acknowledges that there are a number of laser-based droplet sizing instruments but does not specify either type or manufacturer. Womac et al. (1999) suggested that different instruments may give slightly different droplet size spectra, but when both reference nozzles and nozzles to be classified are operated with the same instrument, method, techniques, operator, and similar environmental conditions, as specified in the Standard, then the droplet spectra classifications would be expected to be similar.

The laser probe in this study was mounted on a motorized traverse system that permitted continuous scanning of the spray plume either horizontally or vertically. The laser-imaging zone was 0.74 m downwind from the nozzle orifice except for the straight-stream nozzle trial points that specified no deflector or nozzle discharge angle. The laser-imaging zone was moved to 1.12 m downwind from the nozzle orifice for the straight-stream trial points to permit the spray plume to further develop. The vertical expansion or height of the spray plume for each spray nozzle test condition was determined by a vertical centerline traverse of the spray plume with the laser probe at the designated imaging zone. The top and bottom points of the spray plume were noted when no spray droplets were detected by the laser probe. The height of the spray plume for each nozzle test condition was divided for continuous horizontal sampling scans at 1/8, 3/8, 5/8, and 7/8 of the plume height. Atomization data were continually collected on each of these four horizontal traverses of the spray plume as the laser probe moved from outside of the plume on one side, at each specified height, to outside of the spray plume on the other side. The outside edges of the plume were noted when there were no droplets passing through the plume, as visually observed on the data system monitor.

The number of droplets imaged in the four horizontal traverses of the plume ranged from 16,000 to 45,000. Following the four horizontal traverses of the spray plume, the OAP-1000 software was used to compute $D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$, RS, D_{10}, D_{30}, D_{32}, $D_{N0.5}$, (ASAE Standard S327.2 FEB03) and percentage of the spray volume in size classes 18-100 µm, 100-200 µm, 200-300 µm, 300-400 µm, >400 µm, and <200 µm. Data from three of these four-traverse data scans were recorded and means were computed for the atomization parameters for each of the 27 spray nozzle test conditions or treatments for each nozzle.

Statistical Analysis

Statistical replication implies that, for all test conditions, data are collected once for each test condition, data are then collected a second time for each test condition, and so on. In this study, the test conditions were randomly selected and operated for data collection. Each of the randomly selected test conditions was operated for data collection three separate times before the next randomly selected test condition was operated for data collection. This procedure was used to reduce the multiplicity of equipment setups and time required for each spray nozzle study. Consequently, the atomization parameter means from the three separate data collections are statistical repeated measures, as opposed to statistical replication as outlined in the Standard.

The arrangement of treatments for each spray nozzle study was from a series of multi-factor experimental designs developed by Box and Behnken (1960). Multi-factor experimental designs were originally developed for research in the chemical industry and are common in the mathematical and statistical literature. Handbooks and texts summarize these models

Table 2. Design code and actual variable levels used for 27 trials with eleven fixed-wing aerial spray nozzles to characterize atomization performance.

Design Code	Orifice Number or Orifice Size (X_1)[a]		Spray Discharge Angle (°) (X_2)[a]	Spray Pressure (kPa) (X_3)[a]	Air Speed (km/h) (X_4)[a]
Small Orifice 40° Flat-Fan Nozzle					
	Orifice No.	Model			
-1	4002	2	0	138	161
0	4006	6	45	276	209
+1	4010	10	90	414	257
Large Orifice 40° Flat-Fan Nozzle					
	Orifice No.	Model			
-1	4010	10	0	138	161
0	4020	20	45	276	209
+1	4030	30	90	414	257
80° Flat-Fan Nozzle					
	Orifice No.	Model			
-1	8002	2	0	138	161
0	8006	6	45	276	209
+1	8010	10	90	414	257
CP-03 Nozzle					
	Orifice Size				
-1	0.061 in.		30	138	161
0	0.116 in.		55	276	209
+1	0.171 in.		90	414	257
CP-09 Nozzle					
	Orifice Size				
-1	0.061 in.		0	138	161
0	0.116 in.		5	276	209
+1	0.171 in.		30	414	257
CP-11TT Nozzle with Straight-Stream Tips					
	Orifice Size				
-1	0008		0	138	161
0	0016		10	276	209
+1	0025		20	414	257
Ceramic Disc Orifice 46 Core Nozzle					
	Orifice No.				
-1	2		0	138	161
0	6		45	276	209
+1	10		90	414	257
Disc Orifice 46 Core Nozzle					
	Orifice No.				
-1	2		0	138	161
0	6		45	276	209
+1	10		90	414	257
Disc Orifice 56 Core Nozzle					
	Orifice No.				
-1	2		0	138	161
0	6		45	276	209
+1	10		90	414	257
Disc Orifice Straight-Stream Nozzle					
	Orifice No.				
-1	4		0	138	161
0	8		10	276	209
+1	12		20	414	257
Lund Straight-Stream Nozzle					
	Orifice No.				
-1	6		0	138	161
0	8		10	276	209
+1	10		20	414	257

[a] X_1, X_2, X_3, and X_4 are symbols used for the respective variables in the response equations.

and their uses (Davies, 1963; Box and Draper, 1987). The design selected was a rotatable second-order design for studying four variables, each at three levels, in 27 trials. The design prescribes variable levels for 27 trials or treatments to characterize the response surface created by the nozzle atomization parameters. The general form of the experimental design specifies experimental points coded as −1, 0, and +1 for each variable. The coded experimental design for the 27 trials is shown in the cited reference as well as in Kirk (2002).

The SDTF studies (Hewitt 2001) confirmed the long-held view that spray nozzle characteristics (primarily orifice size and spray discharge angle), spray pressure, and aircraft speed are the dominant factors influencing atomization and spray droplet size from spray nozzles on agricultural aircraft. These four factors were selected as the variables to investigate in these studies. The three actual values for each spray nozzle operating variable were selected from a reasonable aerial-use range for each nozzle. In general terms, the variable values could be called low, medium, and high. For continuous variables, such as spray pressure, aircraft speed, and spray discharge angle, the actual end-point values (−1 and +1 coded values) were equally spaced from the midpoint or medium parameter values (0 coded value). In a few cases, the orifice sizes available for a given nozzle were not equally spaced, so large and small orifices were selected as end-point values, and the midpoint value was selected from the other available orifice sizes for the nozzle that was most closely equidistant from the end points. For the CP-03 and CP-09 nozzles, the manufacturer provided a midpoint orifice diameter equally spaced between the end-point orifice diameters.

The values used for the low, medium, and high test conditions for each nozzle variable are shown in table 2. Atomization parameters $D_{V0.5}$, RS, and percentage of the spray volume <100 μm diameter and <200 μm diameter were selected for analysis and presentation because of the primary importance of these factors to aerial applicators in determining droplet size and percentage of the spray volume that is most subject to spray drift. These data were analyzed by the SAS RSREG procedure in SAS (2001) to develop response relationships for the selected factors. DSC was computed in the models from reference nozzle data and the predicted $D_{V0.1}$ $D_{V0.5}$, and $D_{V0.9}$, as outlined in ASAE S572.

The two small droplet parameters reported in this study (percentage of the spray volume <100 μm diameter and <200 μm diameter) cover the reported historical range for this parameter and give more information than a single value. Values for two parameters can be particularly useful in estimating differences in spray drift potential when differences between treatments or nozzle setups are less apparent in other parameter values. Values of small droplet parameters from spray distributions are highly correlated (Teske et al., 2003), so the specific parameter selected for drift potential estimations should not be a major factor in practical use. Coefficients of determination for measured and model-predicted values of relative span were not as good as for the other parameters; consequently, the defined and computed values for relative span based on RS = $(D_{V0.9} - D_{V0.1})/D_{V0.5}$ were incorporated into the models rather than values predicted by the models for this parameter.

Results and Discussion

The second-order response relationships developed with the specified design and analysis are of the following form:

$$\begin{aligned} Y = {} & A + BX_1 + CX_2 + DX_3 + EX_4 \\ & + FX_1^2 + GX_2X_1 + HX_2^{\,2} + IX_3X_1 + JX_3X_2 \\ & + KX_3^2 + LX_4X_1 + MX_4X_2 + NX_4X_3 + OX_4^2 \end{aligned}$$

where

- Y = predicted atomization parameter based on specification of inputs X_1 to X_4
- X_1 = orifice size (inches for CP nozzles, and number for other nozzles)
- X_2 = spray discharge angle into air stream (°)
- X_3 = spray pressure (kPa)
- X_4 = airspeed (km/h)
- *A* to *O* = coefficients for respective terms of the equation.

The relationships for each nozzle were implemented in Excel (Microsoft Corp.) spreadsheets; an example is shown in figure 1. The coefficients for the respective terms of the atomization parameter equations are listed in the Appendix. These atomization parameter equations must be used with the SI units as noted for the predicted Y values to be correct; different units require different coefficients for each term of the equation. In addition, the equations are not valid outside of the experimental ranges for the X variables, as noted in table 2. Within these constraints, the five equations that may be assembled for each nozzle from the information in the Appendix provide least-squares estimates of the atomization variables for the eleven fixed-wing aerial spray nozzles included in this study. Statistical parameters that characterize the response surface equations for the nozzles were computed and analyzed; brief comments about the statistics are noted in the following sections.

Volume Median Diameter ($D_{V0.5}$) values as measured for the 27 trial points with the 40° flat-fan, 80° flat-fan, and CP-03 nozzles were generally in the range of 120 to 550 μm. The straight-stream nozzles had general $D_{V0.5}$ ranges of 220 to 750 μm. $D_{V0.5}$ for the metal disc-core nozzles were in the general range of 200 to 600 μm, with the 56-core nozzle having about 100 μm smaller diameters than the 46-core nozzle. The ceramic disc orifice 46-core nozzle had a narrower range of $D_{V0.5}$ than the metal 46-core nozzle. Linear terms dominated the response, with quadratic and cross-product terms generally having less influence. Airspeed was the most significant factor in determining $D_{V0.5}$ for each nozzle, except the disc orifice 56-core nozzle for which nozzle angle was most significant. The disc orifice straight-stream nozzle produced the lowest coefficient of variation. The response surface equations had R^2 values of 0.93 to 0.99 for $D_{V0.5}$, indicating that the models gave good estimates of volume median diameter for the measured trial points.

Relative Span (RS) is defined by the equation $(D_{V0.9} - D_{V0.1})/D_{V0.5}$, where $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ are the droplet diameters such that 10%, 50%, and 90%, respectively, of the spray volume is in droplets of smaller diameter. RS is a measure of the range of droplet sizes in the spray spectrum, with smaller numbers indicating a narrower range of droplet sizes accounting for the mid-80% of the spray volume. In early work in this series, model equations were developed for RS. However, in recent work in this series and in this article, model equations were developed for $D_{V0.1}$ and $D_{V0.9}$ along with

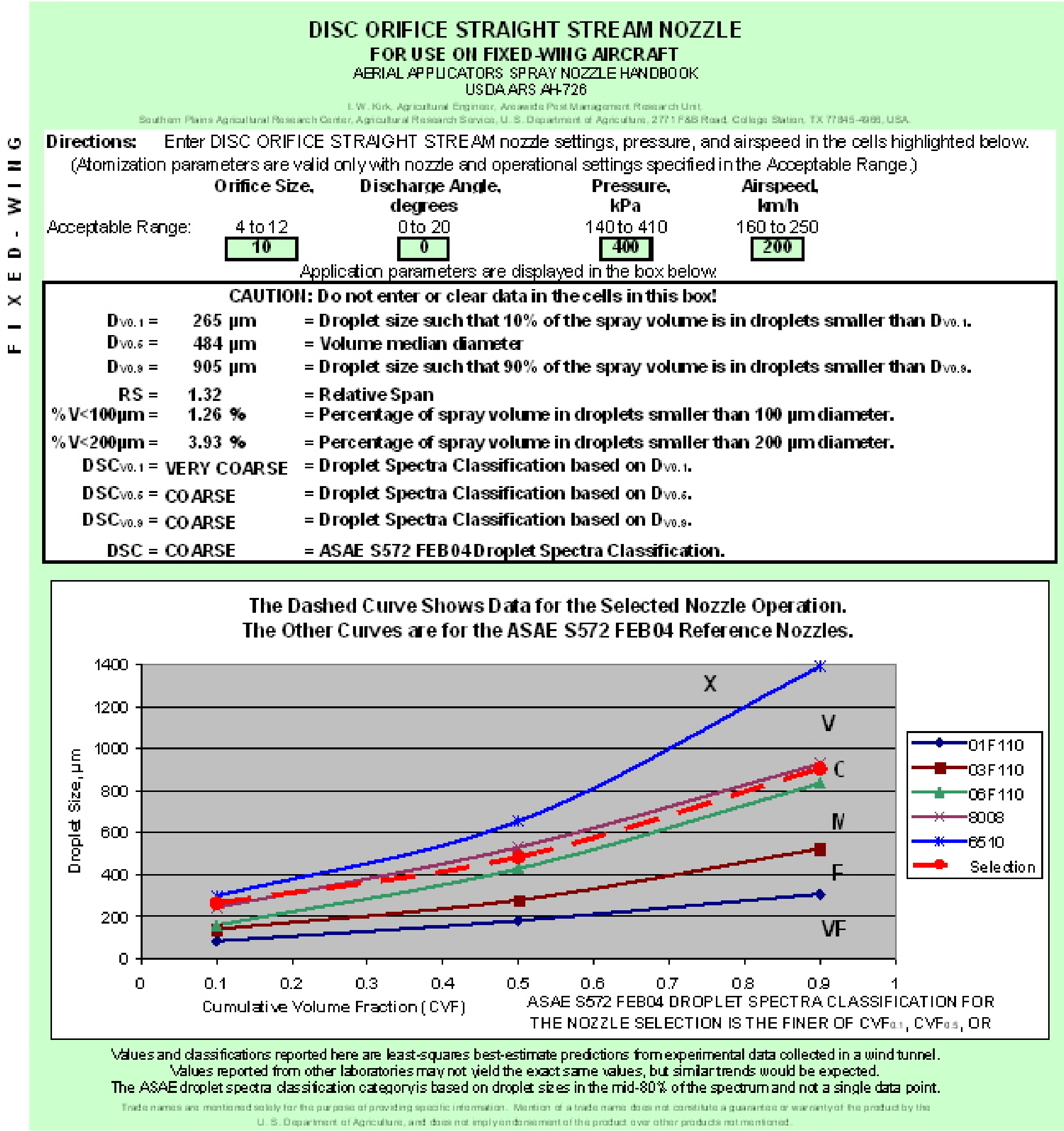

Figure 1. Disc orifice straight-stream nozzle model with operator inputs of orifice size = 10, nozzle discharge angle = 0, spray pressure = 400 kPa, and airspeed = 200 km/h.

$D_{V0.5}$, so RS values were computed from the defining equation.

Percentage of Spray Volume in Droplets Smaller than 100 µm (%V<100 µm) is one of the primary parameters indicative of spray drift propensity of aerially applied agricultural materials. The measured %V<100 µm ranged widely for the different nozzles. The small orifice 40° and 80° flat-fan nozzles and the CP-03 nozzle had %V<100 µm ranging to 40%; the ceramic disc orifice 46-core nozzle and the CP-11TT nozzle with straight-stream tips produced the lowest %V<100 µm for the trial points. Linear, quadratic, and cross-product terms of the equations were significant in describing this parameter, except for the CP-09 and the ceramic disc core nozzles, which had significant linear and quadratic terms only. Airspeed was the most significant factor for describing this response for most of the nozzles; exceptions were the ceramic disc orifice 46-core and the metal disc orifice 56-core nozzles where nozzle angle was most significant, and the large orifice 40° flat-fan nozzle where orifice size was most significant. The CVs for %V<100 µm were lowest for the Lund nozzle and highest for the large orifice 40° flat-fan nozzle. R^2 values for the response surface equations for %V<100 µm ranged from 0.90 to 0.99.

Percentage of Spray Volume in Droplets Smaller than 200 µm (%V<200 µm) also provides a measure of potential spray drift from aerial sprays. The range of %V<200 µm is about double that of %V<100 µm. The small orifice flat-fan, CP-03, and disc orifice 56-core nozzles had the highest %V<200 µm values, and the large orifice 40° flat-fan, CP-11TT with straight-stream tips, and disc orifice 46 core nozzles had the lowest values for %V<200 µm in the trial points. Linear, quadratic, and cross-product terms of the equations were significant in describing this parameter for most of the nozzles; exceptions were the large orifice 40° flat-fan, the 80° flat-fan, and the CP-09 nozzles with only linear and quadratic terms significant in describing this response. Airspeed was the dominant factor for describing this response for most of the nozzles; exceptions were the large orifice 40° flat-fan nozzle and the ceramic disc orifice 46-core nozzle, where nozzle angle was the dominant factor influencing %V<200 µm. CVs for %V<200 µm ranged from 12 to 24 for all nozzles, except for the Lund straight-stream nozzle with a CV of 7.8 and the ceramic disc orifice 46-core nozzle with a CV of 9.7. R^2 values for the response surface equations for %V<200 µm ranged from 0.95 to 0.99 for all nozzles.

Validation of Results

Validation of response relationships is a requisite part of proposing equations that model physical phenomena. It is clear from the R^2 values that the equations modeled the trial points very well. Validation of the equations for points other than the trial points was conducted for the CP-09 nozzle, formerly called the CP straight-stream nozzle (Kirk, 1998). That $D_{V0.5}$ validation exercise demonstrated that the models gave good estimates of performance for points other than the trial points and within the limits of the variables explored in the trials. The approach selected for a broader validation in this study was to compare model predictions with spray droplet spectra data in the published literature, where others have used some of the same spray nozzles and the same or similar experimental setups.

Yates et al. (1985) used 18 data points with three disc core nozzles and two flat-fan nozzles in the range of variables used in the current study. Bouse (1994) used 27 data points with three straight-stream nozzles, one disc core nozzle, and the CP-03 nozzle in the range of variables in the current study. These 45 measured data points and the respective model predictions for the operational conditions associated with the respective points are presented in figure 2. The measured $D_{V0.5}$ for the 27 trial points for the CP-09 nozzle and the respective model predictions for those points are also shown in figure 2, along with four measured and predicted validation points selected to cover the range of $D_{V0.5}$ produced by the CP-09 nozzle. The measure of experimental variability in the 27 trial points is expressed in the R^2 value of 0.96, which is a mid-range R^2 value for $D_{V0.5}$ for the eleven nozzles in the current study. The CP-09 nozzle validation points are actually more tightly grouped around the predicted $D_{V0.5}$ = measured $D_{V0.5}$ diagonal than the trial points. The predicted $D_{V0.5}$ values for the points measured by Yates et al. (1985) are also rather closely aligned with the 1-to-1 diagonal line, except for two outlying data points.

The Bouse (1994) data set has more discrepancy than the other data sets in measured vs. predicted $D_{V0.5}$ values. The model underpredicted the measured values for all of these 27 data points. However, most of the predicted values place the predicted $D_{V0.5}$ in the same DSC category (based only on $D_{V0.5}$) as the measured value. The notable exceptions are the predicted $D_{V0.5}$ values for measured $D_{V0.5}$ values exceeding 450 µm. These points are substantially underpredicted, particularly above $D_{V0.5}$ measured values of 700 µm. All of these substantially underpredicted points are from disc orifice straight-stream nozzles. Bouse (1994) noted that the procedure for scanning the straight-stream nozzles was to scan four times with the laser probe through the center of the spray plume rather than through the plume at 1/8, 3/8, 5/8, and 7/8 of the plume height, as was used consistently in the current study. It is reasonable to expect that laser probe scans at 1/8 and 7/8 of plume height would be of predominantly smaller droplets than scans through the center of the plume. This could be part of the reason for the apparent underprediction of $D_{V0.5}$ values for the straight-stream nozzles in the Bouse (1994) study.

Another factor that could be part of the reason for the apparent underprediction of $D_{V0.5}$ values is the different rates of surfactants that were used in the different studies. In addition, dynamic surface tension values were not specified in the earlier studies, which could have influenced the comparisons. It is notable that in the current study, the actual upper limit of the classification threshold curves has been increased by one standard deviation above the reference nozzle curves, as specified in ASAE S572, which in effect reduces the possibility of higher DSC values. This could also be a factor in the results of similar DSC data comparisons reported by Smith et al. (2005). It is also noteworthy that model underprediction of $D_{V0.5}$ values provides a safety factor when model predictions are used in a regulatory environment for controlling spray drift. These validation results show that spray nozzle models with reasonable statistical bases can be useful tools for aerial applicators to use in estimating DSC for compliance with product label and regulatory agency requirements.

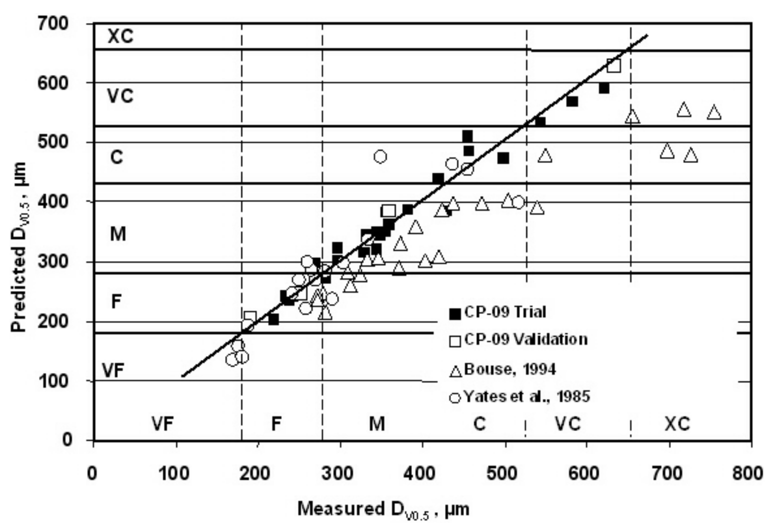

Figure 2. Spray model validation. The diagonal line represents points where the predicted and measured $D_{V0.5}$ values are equal. The dashed vertical lines separate the DSC categories for measured $D_{V0.5}$, and the heavy horizontal lines separate the DSC categories for predicted $D_{V0.5}$.

Summary

Eleven spray nozzle atomization models were developed for spray nozzles in common use in the fixed-wing agricultural aviation industry in the U.S. The models were demonstrated to provide reasonable estimates of spray droplet spectra parameters that are useful in controlling spray drift and complying with product label specifications. The models provide information on droplet size, relative span, percentage of spray volume in the highly driftable portion of the spray spectrum, and droplet spectra classification. This information has been useful to aerial applicators in responsible application of crop production and protection products, and particularly to applicators in states that use these models in regulatory compliance for spray drift mitigation. The models are available in traditional units in the *Aerial Applicators Spray Nozzle Handbook* (Kirk, 2004) or on-line at http://apmru.usda.gov/downloads/downloads.htm.

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References

ASAE Standards. 2004. S572: Spray nozzle classification by droplet spectra. St. Joseph, Mich.: ASAE.

Akesson, N. B. 1954. Drift problems in the application of 2,4-D by aircraft. In *Report of the Second Agricultural Aviation Conf.*, 26-33. Washington, D.C.: USDA Agricultural Research Service.

Akesson, N. B., and R. E. Gibbs. 1990. Pesticide drop size as a function of spray atomizers and liquid formulations. In *Pesticide Formulations and Application Systems*, 1-14. ASTM STP 1078. L. E. Bode, J. L. Hazen, and D. G. Chasm, eds. West Conshohocken, Pa.: ASTM.

Bouse, L. F. 1994. Effect of nozzle type and operation on spray droplet size. *Trans. ASAE* 37(5): 1389-1400.

Bouse, L. F., and J. B. Carlton. 1985. Factors affecting size distribution of vegetable oil spray droplets. *Trans. ASAE* 28(4): 1068-1073.

Box, G. E. P., and D. W. Behnken. 1960. Some new three-level designs for the study of quantitative variables. *Technometrics* 2(4): 455-475.

Box, G. E. P., and N. R. Draper. 1987. *Empirical Model-Building and Response Surfaces*. New York, N.Y.: John Wiley and Sons.

Davies, O. L. 1963. *The Design and Analysis of Industrial Experiments.* London, U.K.: Oliver and Boyd.

Hermansky, C. G. 1998. A regression model for estimating spray quality from nozzle, application, and physical property data. In *Proc. ILASS-Americas*, 60-64. Institute for Liquid Atomization and Spray Systems.

Hewitt, A. J. 1995a. Atomization droplet size spectra of critical parameter range finding substances. Spray Drift Task Force Study No. A91-001. EPA MRID No. 43766500. Washington, D.C.: U.S. EPA.

Hewitt, A. J. 1995b. Atomization droplet size spectra for nozzle and physical property parameter characterization. Spray Drift Task Force Study No. A92-003. EPA MRID No. 44100901. Washington, D.C.: U.S. EPA.

Hewitt, A. J. 1997. Miscellaneous nozzle study. Spray Drift Task Force Study No. A95-010. EPA MRID No. 44310401.0. Washington, D.C.: U.S. EPA.

Hewitt, A. J. 2001. A summary of tank mix and nozzle effects on droplet size. Macon, Mo.: Spray Drift Task Force, Stewart Agricultural Research Services.

Kirk, I. W. 1997. Application parameters for CP nozzles. In *Proc. ASAE/NAAA Joint Technical Session*. ASAEPaper No. AA97006. St. Joseph, Mich.: ASAE.

Kirk, I. W. 1998. Spray quality from CP straight stream nozzles. In *Proc. ASAE/NAAA Joint Technical Session*. ASAEPaper No. AA98002. St. Joseph, Mich.: ASAE.

Kirk, I. W. 1999. Spray quality options with aerial straight stream nozzles. In *Proc. ASAE/NAAA Joint Technical Session*. ASAE Paper No. AA99006. St. Joseph, Mich.: ASAE.

Kirk, I. W. 2002. Measurement and prediction of helicopter spray nozzle atomization. *Trans. ASAE* 45(1): 27-37.

Kirk, I. W. 2004. *Aerial Applicators Spray Nozzle Handbook*. AH-726. Washington, D.C.: USDA Agricultural Research Service.

Picot, J. J. C., M. W. van Fliet, N. J. Payne, and D. D. Kristmanson. 1990. Characterization of aerial spray nozzles with laser light-scattering and imaging probes and flash photography. In *Liquid Particle Size Measurement Techniques*, 142-150. ASTM STP 1083. West Conshohocken, Pa.: ASTM.

SAS. 2001. PC version of the SAS System. Software release 8.02. Cary, N.C.: SAS Institute, Inc.

Skyler, P. J., and J. W. Barry. 1990. Compendium of drop size spectra compiled from wind tunnel tests. Pest Management Report No. FPM-90-9. Washington, D.C.: USDA Forest Service.

Skyler, P. J., and J. W. Barry. 1991. Final report – Compendium of drop size spectra compiled from wind tunnel tests. Washington, D.C.: USDA Forest Service.

Smith, D. B, I. W. Kirk, and J. B. Ross. 2005. Improving the effectiveness of aerial pesticide sprays.Paper ID JAI12166. *J. ASTM International* 2(4): 1-15.

Teske, M. E., A. J. Hewitt, and D. L. Valcore. 2003. Drift and nozzle classification issues with ASAE Standard S572 AUG99 boundaries. In *Proc. ASAE/NAAA Joint Technical Session.* ASAE Paper No. AA03001. St. Joseph, Mich.: ASAE.

Womac, A. R., R. A. Maynard II, and I. W. Kirk. 1999. Measurement variations in reference sprays for nozzle classification. *Trans. ASAE* 42(3): 609-616.

Yates, W. E., R. E. Cowden, and N. B. Akesson. 1985. Drop size spectra from nozzles in high-speed airstreams. *Trans. ASAE* 28(2): 405-410.

Appendix follows.

APPENDIX

The following tables list coefficients and terms for the response equations for the atomization parameters for eleven spray nozzles for fixed-wing aircraft. These coefficients are for use with the X-variables in SI units, i.e., model orifice size or orifice number as specified by the manufacturer (see table 2), deflector angle or nozzle discharge angle in the air stream (degrees), pressure (kPa), and airspeed (km/h). The atomization parameters are defined as follows:

$D_{V0.1}$ = droplet diameter such that 10% of the spray volume is in smaller droplets.

$D_{V0.5}$ = volume median diameter in µm.

$D_{V0.9}$ = droplet diameter such that 90% of the spray volume is in smaller droplets.

%V<100 µm = percentage of spray volume in droplets smaller than 100 µm diameter.

%V<200 µm = percentage of spray volume in droplets smaller than 200 µm diameter.

Small Orifice 40° Flat-Fan Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	625.5454820	26.9713540	-3.0962960	-0.1811590	-3.3745300
$D_{V0.5}$	443.4986980	35.5546880	1.0215280	-0.1346620	-0.5407990
$D_{V0.9}$	894.2052230	79.5585940	-1.9730320	0.5198140	-4.1416380
%V<100 µm	44.9517530	0.3388930	-0.5831200	0.0440410	-0.5245450
%V<200 µm	89.0551690	-0.6392060	-0.7892930	0.0748570	-1.0247510
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-0.7005210	-0.0305560	0.0018110	-0.0018120	-0.0017310
$D_{V0.5}$	-0.9765620	-0.0375000	-0.0170370	0.0108700	-0.0018920
$D_{V0.9}$	-1.7213540	-0.1680560	-0.0171190	0.0117750	-0.0031000
%V<100 µm	0.1338540	-0.0050690	0.0017800	-0.0002760	0.0004960
%V<200 µm	0.3037240	-0.0108470	0.0044220	-0.0009010	0.0005360
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	0.0000088	-0.0651040	0.0111110	0.0012080	0.0038160
$D_{V0.5}$	-0.0003080	-0.0859380	-0.0002310	0.0018120	-0.0030380
$D_{V0.9}$	-0.0006320	-0.1940100	0.0146990	0.0001130	0.0047020
%V<100 µm	0.0000186	-0.0103520	0.0025930	-0.0003490	0.0018660
%V<200 µm	0.0001250	-0.0169400	0.0031720	-0.0008200	0.0038760

Large Orifice 40° Flat-Fan Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	371.343967	13.144271	-2.973958	0.211390	-1.996962
$D_{V0.5}$	1406.353407	-3.103646	-6.520486	0.523777	-7.753689
$D_{V0.9}$	2616.216055	-1.800521	-15.264931	0.916704	-14.929217
%V<100 µm	-5.797369	-0.909292	0.211183	0.020895	0.088818
%V<200 µm	26.954164	-0.775021	-0.191150	-0.011394	-0.209740
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-0.433750	0.041111	-0.000432	0.002717	-0.001570
$D_{V0.5}$	0.010000	0.023333	-0.000494	-0.000906	-0.003422
$D_{V0.9}$	0.094167	0.031667	0.013169	0.001087	-0.008696
%V<100 µm	0.057500	-0.010633	0.000434	-0.000053	0.000025
%V<200 µm	0.049429	-0.008794	0.002812	0.000196	0.000356
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.000525	0.030729	0.007292	0.000566	0.000217
$D_{V0.5}$	-0.000381	0.011979	0.026042	-0.000226	0.011393
$D_{V0.9}$	-0.000168	-0.016146	0.059375	-0.001245	0.023347
%V<100 µm	-0.000025	-0.007125	0.000095	-0.000032	0.000218
%V<200 µm	0.000081	-0.007146	0.001410	-0.000272	0.001317

80° Flat-Fan Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	579.6407340	38.3268230	-2.197338	-0.6568160	-3.322266
$D_{V0.5}$	325.8171480	44.6184900	1.0145830	-0.4847900	0.3011790
$D_{V0.9}$	616.9400680	75.3867190	-0.905903	-0.2221840	-1.688874
%V<100 µm	66.4740740	-2.9669920	-0.444416	0.0386580	-0.634493
%V<200 µm	139.2648550	-9.0052730	-0.748249	0.0869560	-1.251807
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-0.8359370	-0.1055560	-0.002654	0.0203800	-0.001490
$D_{V0.5}$	-1.6510420	-0.0194440	-0.014774	0.0172100	-0.002295
$D_{V0.9}$	-1.9973960	-0.1347220	-0.010535	0.0416670	-0.005032
%V<100 µm	0.1999220	-0.0060830	0.0017000	0.0000498	0.0002270
%V<200 µm	0.5245570	-0.0018470	0.0044380	-0.0003620	0.0004470
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	0.0006430	-0.1080730	0.0121530	0.0013210	0.0044490
$D_{V0.5}$	0.0001420	-0.0976560	0.0002310	0.0023020	-0.004901
$D_{V0.9}$	0.0001730	-0.2096350	0.0105320	0.0011700	-0.000036
%V<100 µm	0.0000076	-0.0014450	0.0022120	-0.0002790	0.0020510
%V<200 µm	0.0000574	0.0030860	0.0025910	-0.0007360	0.0042560

CP-03 Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	507.207097	634.5127	1.128947	0.19542	-2.61015
$D_{V0.5}$	1124.62045	1120.527	-9.00689	0.314185	-4.27365
$D_{V0.9}$	3317.45047	559.0031	-39.5483	1.175376	-14.5792
%V<100 µm	87.353161	135.4538	-0.88393	0.069071	-0.94604
%V<200 µm	126.273214	-12.5953	-0.88346	0.109752	-1.435
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-5041.32	17.66942	-0.03921	1.811594	-0.00599
$D_{V0.5}$	-5385.67	17.61984	0.031857	1.71278	-0.00562
$D_{V0.9}$	-7011.02	47.97521	0.161127	3.359684	-0.01661
%V<100 µm	295.4545	-2.66174	0.005301	-0.11792	0.000437
%V<200 µm	1247.658	-4.71562	0.005575	-0.45191	0.000445
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.00035	-4.07197	0.012273	0.000793	0.000814
$D_{V0.5}$	-0.00012	-5.87121	0.013314	0	0.004919
$D_{V0.9}$	-1.1E-05	-13.1629	0.064328	-0.00166	0.023564
%V<100 µm	3.02E-06	-0.15246	0.002527	-0.00042	0.002837
%V<200 µm	5.97E-05	0.357008	0.004381	-0.00064	0.004349

CP-09 Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	132.141561	2101.288	-2.76716	-0.05485	1.284871
$D_{V0.5}$	1330.57402	2319.024	-8.95069	0.844018	-8.70662
$D_{V0.9}$	2008.29694	8219.109	-18.9133	2.026604	-14.0529
%V<100 µm	38.771321	-146.588	0.107187	0.031674	-0.40026
%V<200 µm	86.602939	-338.829	0.384178	0.072213	-0.90086
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-6955.92	6.987013	0.139	0.230567	-0.00052
$D_{V0.5}$	-9421.49	10.54546	0.288222	-0.6917	-0.00193
$D_{V0.9}$	-36901	31.2987	0.187778	0.592885	0.000973
%V<100 µm	447.5207	-0.58182	-0.00589	-0.02734	0.000114
%V<200 µm	1052.204	-1.05143	-0.01904	-0.06192	-2.9E-06
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	0.000175	-3.31439	-0.01286	0.000415	-0.00658
$D_{V0.5}$	0.000322	-1.42046	-0.00941	-0.00317	0.016547
$D_{V0.9}$	-0.00133	-2.27273	0.022768	-0.00445	0.023492
%V<100 µm	-1.3E-05	0.293561	0.000646	-0.00014	0.001207
%V<200 µm	-1.6E-05	0.660985	0.001953	-0.00038	0.002843

CP-11TT Nozzle with Straight-Stream Tips	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	700.655113	4.180492	-6.14481	0.450257	-3.77653
$D_{V0.5}$	2381.64298	8.830534	-13.8717	2.38559	-18.731
$D_{V0.9}$	2883.61152	41.22733	-38.9578	5.640386	-22.0328
%V<100 µm	0.965896	-0.00456	0.025662	0.001441	-0.01481
%V<200 µm	20.040108	-0.51892	-0.03864	0.030003	-0.24416
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-0.10641	0.075259	0.007083	-0.0038	-0.00091
$D_{V0.5}$	-0.19856	0.109206	0.150833	-0.01491	-0.00018
$D_{V0.9}$	-0.26848	0.975547	0.561667	-0.05819	-0.00036
%V<100 µm	0.000114	-0.0016	7.58E-05	9.59E-07	1.81E-05
%V<200 µm	0.008485	-0.00559	0.000667	0.000107	2.36E-05
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.00026	-0.00662	0.019792	-0.00057	0.006275
$D_{V0.5}$	-0.0003	-0.00596	0.039583	-0.00747	0.039804
$D_{V0.9}$	-0.00178	-0.14027	0.044792	-0.01242	0.045808
%V<100 µm	8.18E-07	0.000109	-3.6E-05	-1.2E-05	5.07E-05
%V<200 µm	2.93E-05	0.001742	0.000859	-0.00028	0.000895

Disc Orifice 46-Core Ceramic Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	393.301107	7.946615	-1.494560	-0.071482	-0.929470
$D_{V0.5}$	915.443540	9.503906	-3.487963	0.049215	-4.438874
$D_{V0.9}$	1604.099175	25.468750	-7.128935	0.454635	-9.358073
%V<100 µm	6.342202	-0.027227	-0.044772	0.003868	-0.067457
%V<200 µm	29.533065	-0.088659	-0.251662	0.047475	-0.422754
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-0.445313	0.038889	-0.001296	0.004529	-0.000644
$D_{V0.5}$	-0.567708	0.075000	0.001502	0.005435	-0.000886
$D_{V0.9}$	0.210938	0.150000	-0.004877	0.054801	-0.001248
%V<100 µm	-0.002630	0.000264	0.000287	-0.000127	0.000030
%V<200 µm	0.167578	-0.023319	0.001852	-0.000829	-0.000012
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.000131	-0.019531	0.003819	0.000830	-0.000109
$D_{V0.5}$	-0.000077	-0.024740	0.010185	0.000302	0.006908
$D_{V0.9}$	0.000000	-0.187500	0.025231	-0.002642	0.019314
%V<100 µm	0.000006	0.000456	0.000152	-0.000040	0.000197
%V<200 µm	0.000057	-0.006654	0.002282	-0.000406	0.001668

Disc Orifice 46-Core Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	676.522316	13.309896	-5.214931	0.254604	-3.454933
$D_{V0.5}$	950.045917	-9.252604	-4.717593	0.076540	-3.340676
$D_{V0.9}$	1744.177156	-22.986979	-9.442708	0.793629	-8.469473
%V<100 µm	44.779209	0.597786	-0.218760	0.048405	-0.587944
%V<200 µm	79.863025	-0.136133	-0.016485	0.055149	-1.046752
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-0.216146	0.018056	0.008416	-0.007699	-0.001208
$D_{V0.5}$	0.119792	0.140278	0.004650	-0.005435	-0.001288
$D_{V0.9}$	1.057292	0.286111	0.007428	0.013134	-0.002536
%V<100 µm	0.082474	-0.018597	0.000564	0.002255	0.000086
%V<200 µm	0.135391	-0.034528	0.000532	0.002631	0.000035
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.000661	-0.028646	0.014005	0.001132	0.003219
$D_{V0.5}$	-0.000510	0.023438	0.011111	0.001963	0.000778
$D_{V0.9}$	-0.000615	-0.013021	0.026042	-0.001057	0.012225
%V<100 µm	0.000083	-0.010391	0.002251	-0.000585	0.002195
%V<200 µm	0.000143	-0.008346	0.002541	-0.000846	0.003901

Disc Orifice 56-Core Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	763.586733	3.811198	-5.275810	-0.001774	-3.288339
$D_{V0.5}$	1278.601780	-33.410156	-8.305324	0.244263	-4.688802
$D_{V0.9}$	2383.630245	-61.621094	-19.45255	1.214372	-10.15488
%V<100 µm	23.387121	1.073008	-0.191289	0.051968	-0.386102
%V<200 µm	41.645922	0.420755	-0.012455	0.106532	-0.754806
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	0.052083	0.106944	0.008004	0.008605	-0.001932
$D_{V0.5}$	1.093750	0.397222	0.013272	0.004529	-0.002496
$D_{V0.9}$	2.067708	0.862500	0.035350	0.009511	-0.003140
%V<100 µm	0.021615	-0.016778	0.000644	-0.000063	0.000122
%V<200 µm	0.071615	-0.035458	0.000662	-0.000856	0.000093
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.000435	-0.040365	0.011921	0.001472	0.002532
$D_{V0.5}$	-0.000637	-0.006510	0.016435	0.001510	0.003689
$D_{V0.9}$	-0.001532	-0.045573	0.038657	-0.000302	0.013057
%V<100 µm	0.000057	-0.005716	0.001900	-0.000452	0.001504
%V<200 µm	0.000120	-0.001172	0.002297	-0.000931	0.003074

Disc Orifice Straight-Stream Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	373.610569	17.593750	-1.035417	0.340202	-0.925998
$D_{V0.5}$	1995.949707	8.654948	-4.609896	1.384322	-13.96018
$D_{V0.9}$	2938.227376	65.868490	-7.382813	2.816161	-21.36274
%V<100 µm	15.736694	-0.038242	-0.108667	0.020872	-0.219267
%V<200 µm	39.980481	-1.648854	-0.316177	0.052116	-0.480452
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	-1.242188	-0.062500	-0.018750	0.004982	-0.010688
$D_{V0.5}$	-1.898438	0.125000	0.030000	-0.014493	-0.006703
$D_{V0.9}$	-4.882813	0.200000	0.097500	-0.013587	0.001630
%V<100 µm	0.048099	0.002250	-0.000029	-0.000462	0.000629
%V<200 µm	0.156146	0.007937	-0.000217	-0.001236	0.000879
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.000446	0.010417	0.018750	0.000981	-0.004015
$D_{V0.5}$	-0.000407	0.095052	0.018229	-0.002680	0.024360
$D_{V0.9}$	-0.001050	0.048177	0.007813	-0.005774	0.038140
%V<100 µm	0.000030	-0.003424	-0.000167	-0.000244	0.000999
%V<200 µm	0.000077	-0.003021	0.000510	-0.000588	0.002147

Lund Straight-Stream Nozzle	Coefficient (Term)				
	A (constant)	*B* (X_1)	*C* (X_2)	*D* (X_3)	*E* (X_4)
$D_{V0.1}$	177.629521	18.809896	8.305729	0.249623	0.129268
$D_{V0.5}$	1753.847512	9.617187	2.747396	1.236828	-12.36748
$D_{V0.9}$	4412.305809	-137.390625	7.140104	2.355752	-27.97389
%V<100 µm	18.768520	0.213646	-0.340042	0.023953	-0.256653
%V<200 µm	47.034529	-1.776198	-0.800807	0.073721	-0.543231
	F (X_1^2)	*G* (X_2X_1)	*H* (X_2^2)	*I* (X_3X_1)	*J* (X_3X_2)
$D_{V0.1}$	0.197917	-0.725000	-0.034583	-0.005435	-0.008696
$D_{V0.5}$	-1.020833	-0.112500	0.100417	-0.004529	-0.002899
$D_{V0.9}$	1.114583	0.487500	0.262083	0.049819	-0.014855
%V<100 µm	-0.024167	0.039875	0.002021	0.000525	0.000647
%V<200 µm	0.011667	0.075125	-0.000646	-0.000408	0.000658
	K (X_3^2)	*L* (X_4X_1)	*M* (X_4X_2)	*N* (X_4X_3)	*O* (X_4^2)
$D_{V0.1}$	-0.000057	-0.059896	0.002604	0.000377	-0.004159
$D_{V0.5}$	0.000225	0.007813	-0.014062	-0.004340	0.024595
$D_{V0.9}$	0.000674	0.348958	-0.056771	-0.009737	0.052337
%V<100 µm	0.000015	-0.001979	-0.000875	-0.000257	0.001142
%V<200 µm	0.000029	0.004948	0.000224	-0.000574	0.002220